論文

Global Vegetation Index と気候学的推定法による蒸発散量計算値の対応関係

Relationship between the Global Vegetation Index and the Evapotranspirations derived from Climatological Estimation Methods

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Abstract: Vegetation index is the most practical product of the satellite remote sensing. Recent studies reveal that the vegetation index can be related to the transpiration.

The correlation of seasonal trend and annual integrated values of the Normalized Difference Vegetation Index (NDVI), included in the Global Ecosystem Database supplied by NOAA-EPA, with evapotranspiration estimates are tested to examine the possibility of the vegetation index as a model parameter to estimate areal evapotranspiration.

In the mid latitudes, seasonal trend of monthly NDVIs is well correlated to that of evapotranspiration. Annual integrated NDVIs can be used as the index of evaporation ratio, namely, the ratio of actual to potential evapotranspiration. These results can only be applied in the mid latitudes. There is no clear relationship between NDVI and evapotranspirations in the low latitudinal region, especially in the humid tropics.

論文要旨

植生指標は衛星によるグローバルデータセットとして最も実用的なプロダクトであるうえに，蒸散速度との関係が実験的にも理論的にも確かめられている。そこで，アジア地域を対象として，NOAA-EPA 作成の Global Ecosystem Database に含まれている植生指標の季節変化および年間積算値と，気候学的推定法で求めた月蒸発散量計算値および年蒸発散量との関係について検討を行った。

その結果，中緯度に限り両者の季節変動の相関が高いことが明らかとなった。また，月植生指標の年積算値は実蒸発散量計算値との相関が高く，植生指標データセットから蒸発比（実蒸発散量／可能蒸発散量）を推定する可能性が示唆された。ただし，低緯度，特に湿潤熱帯では両者の関係は明瞭ではなかった。

1. Objectives of the Study

Estimating evapotranspiration is associated with the understanding of the partitioning ratio of solar energy to the sensible and latent heats at the ground surface. The change in this ratio causes the environmental change of the region, such as regional warming, desiccation, and so on. As the evapotranspiration is determined not only by climatic conditions but also by land cover, evapotranspiration changes with the land cover alteration.

Human beings have been altering land surface during last several thousands of years. This change must have affected on the evapotranspiration. To reveal the amount of the influences to the evapotranspiration by man's developing activities is the main interest of the author. An evapotranspiration model of which parameters are related to the surface characteristics can assess the change in evapotranspiration with the change in land cover.

The vegetation index products are easily obtained from several earth observation satellites, and recent studies show that there is a considerable correlation between vegetation index and transpiration. So the

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usage of the vegetation index as a model parameter is examined for the areal evapotranspiration modeling.

The objective of this study is to confirm the correlation between evapotranspiration and vegetation index over extensive area by using global data sets. There are several methods to estimate evapotranspiration using climatological data. A comparison of evapotranspirations is firstly made to confirm differences among the five selected methods, and the correlations between evapotranspirations and vegetation index is examined to reveal whether the vegetation dynamics can be used to estimate actual evapotranspiration.

2. Previous Studies

After LANDSAT-1 (ERTS-1) launched in 1972, the studies on the vegetation using remote sensing data experienced great progress. Initially, the correlations between the simple ratio or the normalized difference of the reflected near-infrared and visible radiances and leaf area index (LAI) or bimass were investigated by many researchers (for example, Asrar et al., 1984 ; Tucker et al. 1981).

In the next step of the application, the vegetation index was related to the photosynthesis, and the study proceeds to the estimation of net primary production (Monteith, 1977 ; Goward et al., 1985 ; Heimann et al. 1986 ; Fung et al. 1986).

Sellers (1985, 1987) gave theoretical basis to the relationship between the vegetation index and photosynthesis or net primary production, and showed that vegetation index has a linear relationship against the absorbed photosynthetic active radiation (APAR).

APAR is closely related to water losses, i. e. transpiration of the vegetation. Running and Nemani (1988) showed high correlation between annual integration of the normalized vegetation index (NDVI) and annual transpiration. They examined the trends of weekly NDVIs and transpirations derived from their model (FOREST-BGC). Kerr et al. (1989) showed that NDVI was closely correlated with the actual evapotranspiration with a time lapse of 20 days. Box et al. (1989) also showed that annually integrated NDVIs is closely related to annual totals of actual evapotranspiration. These studies reveal the possibility to estimate areal actual evapotranspiration by satellite derived vegetation index products.

3. Data and Methods

3.1 Methods to estimate evapotranspiration

Evapotranspirations are calculated by several empirical and semi-empirical methods using FAO-CLIM, agroclimatic data base created by Food and Agriculture Organization. FAOCLIM contains monthly averages of eleven climatological elements, which enables the calculation of complicated evapotranspiration models.

The length of observation durations varies from station to station in FAOCLIM. It contains only the starting year of the observation and the period of observed duration. Evapotranspiration, however, is a relatively stable element in the water balance equation. It is assumed that the difference in the period of the statistics calculations causes no significant errors.

Thornthwaite, Penman, Priestley and Taylor (PT), Brutsaert and Stricker (BS) and Morton methods are used to estimate evapotranspiration. All methods require only the climatological data easily available. As for the calculation methods, refer to the original papers or Kondoh (1994a). Brief explanations are presented below.

Thornthwaite method (Thornthwaite, 1948) is a fully empirical method which requires only monthly air temperatures. Penman (1948, 1963) combined the energy-budget and mass-transfer approaches to derive well known Penman formula. Thornthwaite and Penman methods produce a potential evapotranspiration (PET). It must be noted that actual evapotranspiration is often limited below PET by soil moisture status and physiological activity of the vegetation. Moreover, PET is not the upper limit of the actual evapotranspiration due to the existence of canopy resistance and advection (Kayane, 1980).

PT method (Priestley and Taylor, 1972) is the product of equilibrium evaporation (Slatyer and McIlroi, 1961) and a constant α , and is called as potential evaporation. In this study, the constant α of 1.26 is applied to the radiation term in Penman method.

BS (Brutsaert and Stricker, 1979) and Morton (Morton, 1983) methods apply complementary relationship (Bouche, 1963 ; Morton, 1978, 1983) to incorporate the control of soil water deficit to the evapotranspiration. In a sense, they produce actual evapotranspirations. BS method uses the PT method as a wet environmental evapotranspiration, and Penman method as the potential evapotranspiration in the complementary relationship. Although the general form of the Morton method is identical to the BS method, it uses many empirically derived equations parametarised in U.S.A., Europe and Africa.

Albedo is assumed to be 20% in the Penman, BS and PT methods. Penman (1964) and Chang (1970) gave 25% as the albedo of the vegetation in the mid latitudes. Chang (1970) estimated the albedo as 15% for vegetation in low latitude. Constant albedo of 20% may leads somewhat larger evapotranspiration in the mid latitudes, and smaller value in low latitude.

3.2 Vegetation index data

EOS-NESDIS Monthly Experimental Calibrated Global Vegetation Index is used as vegetation index data. It is contained in the Global Ecosystem Database Version 1.0, which is called MEV for brevity here.

MEV is supplied as monthly vegetation index from April, 1985 to December, 1990. Image size is 1080 lines x 2160 pixels. Its spatial resolution is 10 minutes, which correspond to about 20 km on the equator.

Calculated evapotranspirations are climatological values, namely the long term average of the evapotranspirations. Monthly average vegetation index images are processed using monthly MEVs from 1986 to 1990.

The locations of the stations in FAOCLIM can easily be correlated with the pixel of the monthly average MEVs using latitude and longitude coordinates. The evapotranspirations at the FAOCLIM stations are compared with the spatially corresponding MEV data.

4. Results and Discussions

4.1 The comparison of evapotranspirations

The evapotranspiration models used here are full- or semi-empirical models. They have a advantage that estimate of evapotranspiration is available without specific observations, but the area applicable is restricted because they contain empirical equations parametalized in a specific area. The model outputs are compared before correlated to the vegetation index.

Figure 1 shows latitudinal profile of calculated evapotranspirations from Wakkanai, Japan (45.42N, 141.68E) to Palembang, Indonesia (2.90S, 104.70E) along Pacific Ocean and South China Sea. Figure 2 also shows NS profile form Mohe, China

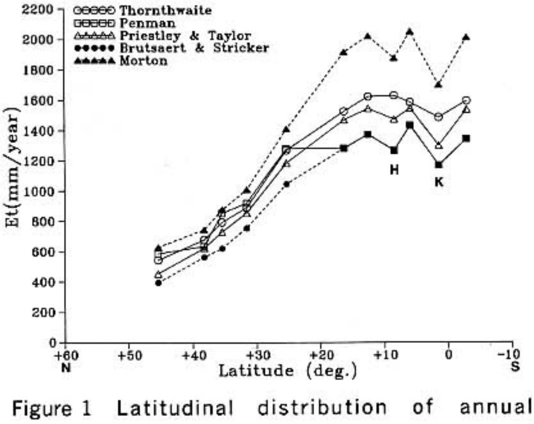

Figure 1 Latitudinal distribution of annual evapotranspirations.
H:Hinatuan (Philippine), K:Kuching (Malaysia)

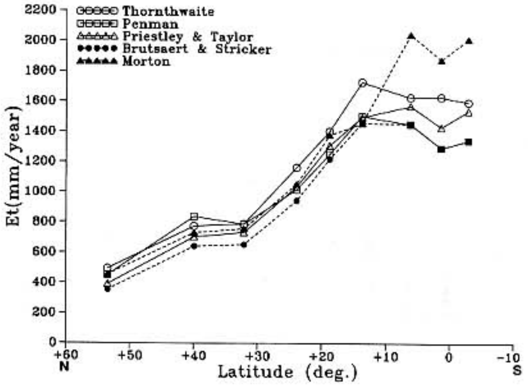

Figure 2 Latitudinal distribution of annualevapotranspirations.

(53.47N, 122.37E) to Palembang through the Asian continent. There are no significant differences to the north of 20° N in Figure 1 and to the north of 10° N in Figure 2. The adjustment for small discrepancies in the mid latitudes is possible by the selection of the appropriate albedo value in Penman, PT and BS methods. Near the equator, Morton method shows rather high evapotranspiration.

Annual precipitation exceeds 4,000 mm in Hinatuan, Phillippin (8.43N, 126.33E) and Kuching, Malaysia (1.48N, 110.33E) plotted in Figure 1. At these stations, the differences between Thornthwaite and Penman methods become large. Because the increase in precipitation generally causes the decrease in net radiation (Kayane and Takeuchi,

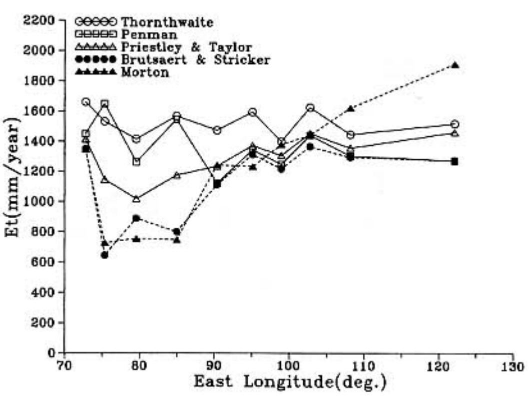

Figure 3 Longitudinal distribution of annualevapotranspirations.

1971), Thornthwaite method produces higher estimate than Penman method. It suggests that Thornthwaite method tends to produce higher estimate in the humid tropics.

Figure 3 shows longitudinal profile from Bombay, India (18.90N, 72.80E) to Casiguran, Philippine (16.28N, 122.13E). In semi-arid region of Decan Highland, around 80°E, Thornthwaite and Penman methods produce higher estimates which exceed annual precipitation. These methods calculate "potential evapotranspiration" by definition, which apparently exceed "actual evapotranspiration". So care must be taken when compared them with the index derived from satellite data which expresses the vegetation activity at the satellite overpass.

In Indochina Peninsula, around 100°E, the differences among the values are small. In Philippine, around 120°E, Morton method produces higher value.

We cannot discuss about which methods is correct without measured evapotranspiration. There is a standard to examine the accuracy of the estimates. Because the increase in precipitation causes the decrease in radiation as described before, the maximum evapotranspiration may exists (Kayane and Takeuchi, 1971).

Solomon (1967) shows the scattergram between annual precipitation and evapotranspiration estimated from water balance method in tropical watersheds. The maximum evapotranspiration in the tropics can be estimated to be about 1,600 mm/year from the scattergram. Kayane (1989) states that the upper limit of evapotranspiration in low latitudinal area is about 1,600 mm/year based on the evapotranspirations estimated from the water balance method in many watersheds in Sri Lanka.

This upper limit standard suggests that Morton method produces erroneously higher evapotranspiration in the humid tropics. This is partly because of the underestimation of albedo value in the Morton method in the humid tropics (Kondoh, 1994a).

4.2 Relationship between seasonal trend of

monthly NDVIs and that of evapotranspirations

Regression analyses between monthly NDVI values at the stations and five evapotranspiration estimates are performed. Correlation coefficients are plotted on the map. For brevity, the maps for Thornthwaite and Morton methods are shown in Figures 4 and 5, because distribution patterns are nearly the same among five methods.

The stations with correlation coefficient over 0.8 are located in the area to the north of around 20 or 30°N. Correlation coefficients rapidly drop in south of 20°N. This boundary corresponds well to that of tropical and temperate vegetation types (Ohsawa,

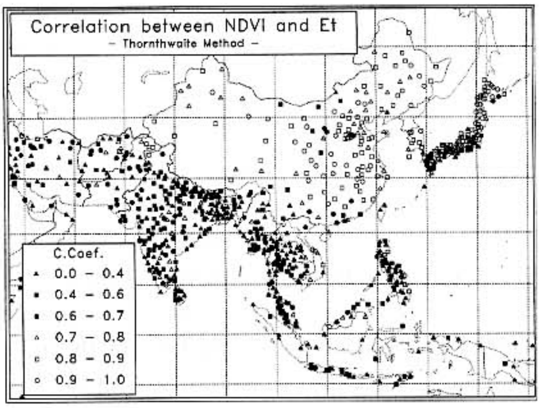

Figure 4 Distribution of correlation coefficients between NDVI and evapotranspirations estimated from Thornthwaite method.

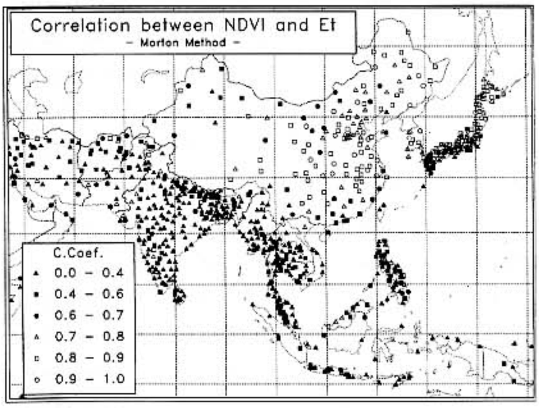

Figure 5 Distribution of correlation coefficients between NDVI and evapotranspirations estimated from Morton method.

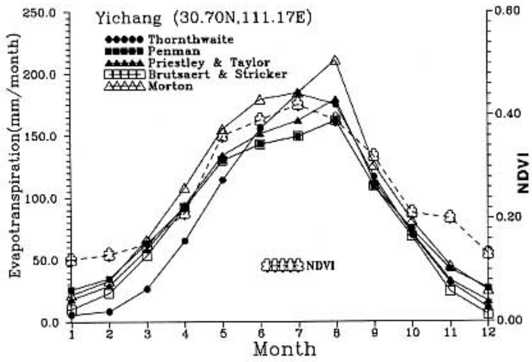

Figure 6 Monthly evapotranspirations (Et) and Normalized Vegetation Index (NDVI) at Yichang, China.

1990, 1993).

Temperate forest shows clear phenology. The phase of the variation is the same as that of air temperature or net radiation. This explains the high correlation between NDVI and evapotranspirations in the mid latitudes.

The small correlation coefficients in the tropics are explained as follows. First point is that evergreen forests in the tropics show less seasonal variability in physiological activities. Second is that the vegetation index has a certain saturation level, and it is possible for NDVI to saturate in the tropics.

As an example of the station with high correlation coefficient, Figure 6 shows the seasonal trends of monthly NDVIs and evapotranspirations at Yi-

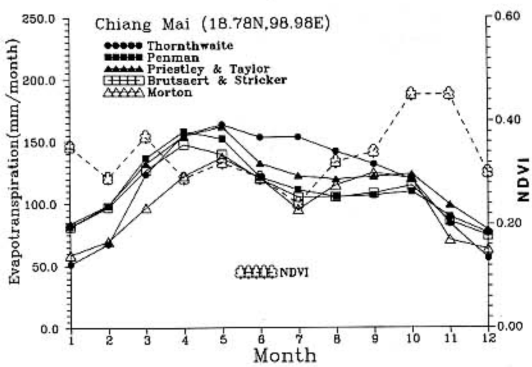

Figure 7 Monthly evapotranspirations (Et) and Normalized Vegetation Index (NDVI) at Chang Mai, Thailand.

chang, China (30.7N, 111.2E). The correlation coefficients are over 0.95 for five methods. It suggests the existence of a simple rule for estimating evapotranspiration from the vegetation index in the mid latitudes.

Figure 7 shows the monthly NDVIs and evapotranspirations at Chiang Mai, Thailand (18.8N, 99.0E), as an example of the station with low correlation. The peaks of evapotranspiration trends do not agree with that of NDVI, and maximum NDVI appears after the rainy season.

Phenology of vegetation has high correlation to the air temperature or net radiation in the mid latitudes, while the relationship to the precipitation is important in the low latitudes. Difference in vegetation type which adopts different climatic conditions, is most important to the analysis on the relationship between NDVI and evapotranspiration.

In the mid latitudes, NDVI and evapotranspirations have good correlation, however, the gains in regression equations show large variation. The regression analysis is tested between the gains and the climatological elements. As a result, no good relationship is found among them except Morton method. There is a weak trend in Morton method that the gain decreases with annual precipitation. This shows that the arid condition produces less evapotranspiration per unit of NDVI, as described in Running and Nemani (1988).

4.3 The relationship between annual integrated NDVIs and annual evapotranspirations

Figures 8 and 9 are the scattergrams between annual integrated NDVIs and annual evapotranspirations by Thornthwaite and Morton methods in Monsoon Asia, with symbolism for the East, Southeast and South Asia. Annual integrated NDVIs is the annual sum of monthly NDVI values. For these results, NDVI is truncated to 0.0 whenever NDVI is smaller than 0.0, because minus NDVI contains no spectral signals on vegetation. The stations within 20 km from the coast line are discarded due to proximity to the ocean which could lead to mixed pixels (sea and land).

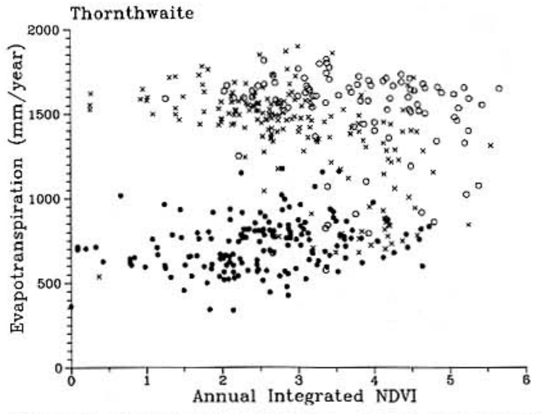

Figure 8 Scattergram between annual integrated NDVIs and evapotranspiration by Thornthwaite method. ● : East Asia (R^2= 0.10), ○ : Southeast Asia (R^2= 0.03), × : South Asia (R^2= 0.19).

Figure 8 is the plots for Thornthwaite method. The scattergrams for Penman and PT methods show similar patterns, and are omitted for brevity. These methods calculate "potential evapotranspiration" and "potential evaporation" by definitions. There are no obvious correlations between annual integrated NDVIs and annual evapotranspirations. These methods produce large evapotranspiration where vegetation is sparse, because of high air temperature or high drying power.

The pixel value of NDVI is considered to contain the information on the "state" or "rate" of vegetation within the pixel element at the satellite overpass (Sellers, 1987). This means that NDVI cannot be an index concerning the potential evapotranspiration or potential evaporation.

It is interesting that the cluster plots can divided into two distinct groups at annual Et of around 1,200 mm/year. The boundary is located near southern national boundary of China, around 20 to 30°N, and is well correspond to the boundary between temperate and tropical vegetation type as is the case of the correlation of their seasonal trends (Figures 4 and 5).

Figure 9 shows the cluster plot for Morton method. In the mid latitudes, there seems to be a strong correlation between annual integrated

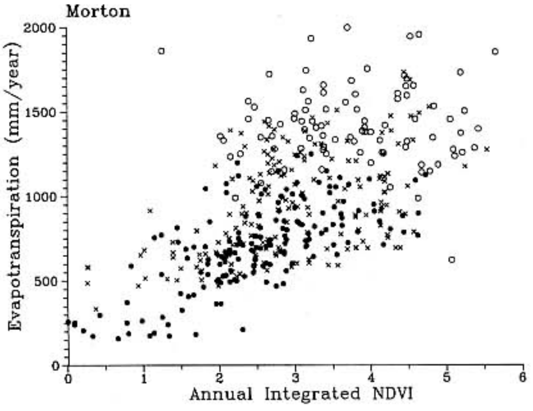

Figure 9 Scattergram between annual integrated NDVIs and evapotranspiration by Morton method. ● : East Asia (R^2= 0.45), ○ : Southeast Asia (R^2= 0.00), × : South Asia (R^2= 0.25).

NDVIs and annual evapotranspiration. Brutsaert & Stricker method, which is not presented here, also shows weak correlation against annual integrated NDVI in the mid latitudes.

In the East Asia group (●) and South Asia group (×), annual evapotranspiration increases with annual integrated NDVIs. No correlation, however, is found in the group of Southeast Asia (○). Morton method incorporates the complementary relationship to adjust the decrease of evapotranspiration due to moisture deficiency. This relationship suggests that annual integrated NDVIs can be an index to the annual actual evapotranspiration.

The vegetation index become small with decreasing evapotranspiration, or with increasing aridity. Tucker (1979) presents the observational data which show inverse relationship between leaf water content and vegetation index. If the leaf water content can be regarded as an index of water stress, vegetation index of the plant suffering water stress become low.

Several researches reveal the correlation between vegetation index and leaf area index (LAI). The amount of leaf is inversely related to the canopy resistance, so evapotranspiration increases with leaf density. Some pixel elements of the GVI are a mixel of vegetation and other features, so the NDVI in the GVI is considered to indicate the amount of leaf in the pixel element. In general, transpiration is greater than surface evaporation in the vegetated area, so we can understand the fact that there is high correlation between the NDVI and actual evapotranspiration.

4.4 Estimation of actual annual evapotranspiration by NDVI

The above result suggests that the vegetation index can be an index of evaporation ratio (the ratio of actual evapotranspiration to the potential one) in the mid latitudes. Thornthwaite and PT methods require fewer input parameters than Morton method, and it is easy to apply them using current global datasets. For example, Ahn and Tateishi (1994) calculates the PT method using datasets contained in the GEDB CD-ROM. However, they produce potential evapotranspiration (or evaporation) not the actual one. The weight is attached to the potential evapotranspirations to get the actual evapotranspiration.

The following equation is used as a weighting function.

$$w = SQRT\ (NDVI/NDVI_{sat}),$$

where $NDVI_{sat}$ is a saturation level of monthly NDVI. Because NDVI-LAI curve shows a saturation curve, passing through the zero-zero point and with an upper asymptote (ex. Nemani and Running, 1989), weighting factor, w, is extracted square root. This procedure leads to better correlation coefficients than linear weighting function.

Morton (1983) shows the table comparing calculated annual evapotranspirations with measured one by water balance method in the experimental watersheds over the world (except humid tropics). It is considered that the method is successfully estimated the actual evapotranspirations in the mid latitudes, so Morton method is used as a standard evapotranspiration. NDVIsat is determined empirically by adjusting the weighted evapotranspiration to the Morton method.

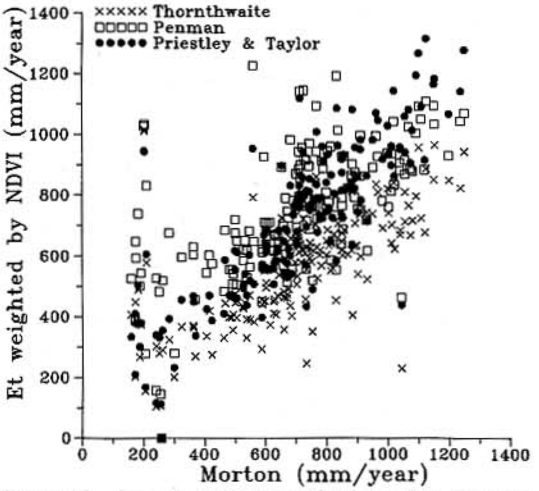

Figure 10 Annual evapotranspirations by Thornthwaite (×), Pen man (□) and Priestley and Taylor (●) methods weighted by NDVI against Morton method. Stations in East Asia are used for the analysis.

Figure 10 shows the plots of weighted evapotranspirations against Morton method for East Asia group (● in Figures 8 and 9). The relationships are nearly linear. R^2 for Thornthwaite and PT methods are 0.72 and 0.73, respectively. R^2 of 0.15 for Penman method is small. It is caused by the aerodynamic term which produce higher evapotranspiration in arid condition.

If Morton method successfully estimates the actual evapotranspiration, the results show that NDVI can be used to calculate annual actual evapotranspiration from the potential one. In other word, the reduction in evapotranspiration with decreasing water availability can be incorporated to the Thornthwaite or PT methods with the use of NDVI. Kondoh (1994b) shows the map of annual actual evapotranspiration by Thornthwaite method weighted by ΣNDVI. It is important that the current vegetation/land cover can be reflected in the resultant evapotranspiration maps.

5. Final Remarks

There are two main conclusions in this study. First one is that seasonal trend of NDVI is well correlated to that of evapotranspiration in the mid latitudes. Second is that annual integrated NDVIs can be used as the index of evaporation ratio, namely, the ratio of actual to potential evapotranspiration. These simple relationships between practical satellite remote sensing products and evapotranspiration are important to estimate areal evapotranspiration in continental or global scales.

Current Global Vegetation Index has many problems concerning subsampling method, calibration of sensors, and so on (Goward et al., 1993). Although detailed analysis must be done using unsubsampled and calibrated vegetation index products, the results obtained in this study reveal the availability of NDVI to estimate actual evapotranspiration over extensive area.

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